

THE RELATIONSHIP BETWEEN THE CHEMICAL AND PLASTIC PROPERTIES OF
ALABAMA MEDIUM-VOLATILE COALS AND THEIR CARBONIZATION BEHAVIOR

B. R. Kuchta and J. D. Clendenin

United States Steel Corporation
Applied Research Laboratory
Monroeville, Pa.

Because coke quality is a significant factor in the efficient operation of blast furnaces, coke-plant operators are continually striving to produce the highest quality coke possible. No less important to the operators, however, are those characteristics of the coals or coal blends that influence the coking pressure and the ease with which each charge can be pushed from the oven. The difficulties in pushing coke from the ovens have been classified¹⁾* into two general categories: (1) those inherent in the particular coals or coal blends and (2) those due to plant practices. Apart from the difficulties attributable to plant practices, insufficient contraction of the coking charge at the end of the coking cycle is undoubtedly the most common reason for coke being hard to push from the oven. Insufficient contraction can be caused by either a lack of sufficient contraction inherent in the coal or coal blend, or by incomplete carbonization of the coal charge in the oven.

The expansion-contraction data obtained from a sole-heated oven is usually used to provide an indication of this aspect of the coking behavior of coal charges. As was pointed out recently,²⁾ a minimum contraction of 7 per cent in the sole-heated oven at the plant-operating bulk density is considered the limiting value for avoiding trouble caused by pushing difficulties. Other investigators^{3,4)} have shown that volume-change characteristics (or expansion-contraction properties) are related to the chemical and plastic properties of a wide range of coals. However, investigations⁵⁾ on coking-strength evaluations indicated that more workable relationships could be established if the correlations were confined to a narrower range of coals or coal blends. Accordingly, U. S. Steel's Applied Research Laboratory undertook a program to determine whether this concept was applicable in relating the volume-change characteristics of several Alabama medium-volatile coals to their chemical and plastic properties. Such a relationship would be extremely useful at U. S. Steel's Fairfield plant in Alabama.

Source and Identification of Coals

Thirty coal samples, 5 washed and 25 raw-mine samples, were examined for chemical, plastic, coking, and volume-change properties. The samples were obtained from the Pratt, American, and Mary Lee seams of the Warrior Coal Field in Alabama. The 5 washed samples were obtained by taking representative gross samples of about 250 pounds each of freshly mined coal from between 5 and 10 mine cars at the unloading station of each of 5 mines. These samples were crushed to pass 2-inch square openings and were experimentally washed to approximate the actual commercial preparation of the respective coals. The 25 raw samples were taken from different zones in the vertical face of the coal seam at specific site locations in the three seams, see Table I. Each sample was chosen by visual inspection of bright and dull coal in the seams, to give differences in coal type.

Experimental Procedures

In the preparation of the charges for carbonization tests, all coals were dried to a nominal moisture content of 1 per cent and pulverized to a 1/4-inch top size.

* See References.

The carbonization tests were conducted in the 30-pound test oven and in a sole-heated oven at the Applied Research Laboratory. Tests in the 30-pound test oven were conducted at the fast rate (1850 F) described in a previous publication.⁵⁾ The sole-heated oven used is similar in construction to the Bureau of Mines sole-heated oven⁶⁾ except that it is heated by four Globar heating elements and changes in the volume of the coal charge are continuously recorded by means of an inductance-bridge type instrument (also known as a differential transformer). The cokes produced in these ovens were tested according to the U. S. Steel Modified Tumbler Test procedure.⁵⁾

The proximate analyses and mineral-matter contents of the various samples are shown in Table I. For purposes of comparison, it was necessary to correct the as-measured volatile-matter contents of the coals to the Parr true-volatile-matter content basis.⁷⁾ The plastic properties of the coals are given in Table II. The volume change (expansion or contraction) in the sole-heated oven and the relative strengths of cokes from this oven are presented in Table III. The coking pressures and the strengths of the cokes from the 30-pound test oven are listed in Table IV.

In the sole-heated oven tests, significant differences in oven bulk densities were noted for various charges, with coals of lower ash content showing generally lower bulk densities than coals of higher ash content, as illustrated in Figure 1. Moreover, because the coals of higher ash content were more resistant to pulverization, the coarseness of the higher ash coals, expressed as the per cent retained on 8 mesh, was greater for these coals than for those of lower ash content, Figure 2. Therefore, because bulk density affects the as-measured volume change, these values were corrected⁸⁾ to a constant bulk density of 55 pounds per cubic foot and to 1 per cent of the as-charged coal retained on 4 mesh, to present the test results on a comparative basis. A reference bulk density of 55 pounds per cubic foot was used because this is approximately the highest level that can be attained with air-dried coal in commercial practice. Bulk density also influences coking pressure, but at the lower pressures encountered with these coals the effect is small.

Chemical and Plastic Properties of Coals

Most of these coals are classified as medium-volatile in rank. A few of the raw mine samples and the Pratt seam, Mine A, washed samples were on the borderline between medium-volatile and high-volatile A in the American Society for Testing Material (ASTM) classification.⁹⁾ The ash content of the raw samples ranged from about 3 to almost 26 per cent, and the sulfur contents from 0.6 to 5.6 per cent, Table I. The ash contents of the washed coals ranged between 7 and 11.7 per cent, and the sulfur contents between 0.8 and 1.7 per cent. The Pratt-seam coals showed the highest sulfur contents.

The plastic properties of these coals ranged from medium to high fluidity, Table II. When the sole-heated-oven volume-change results, Table III, were plotted against the Gieseler maximum fluidity, two principal behavior groups were evident, Figure 3. All coals having maximum fluidities above 10,000 dial divisions per minute (ddpm) were contracting within a range from about 5 to 30 per cent. Those coals having maximum fluidities below 10,000 ddpm ranged from mildly contracting, through neutral, to moderately expanding at about 2500 ddpm fluidity. The raw and washed Pratt Seam samples from Mine A; the raw American Seam, Site No. 2 samples; the raw Mary Lee Seam, Site No. 1 samples; and the washed Pratt Seam, Mine B samples all showed fluidities above 10,000 ddpm. The remaining samples showed lower fluidities. Therefore, the differentiation of coals observed as a result of the Gieseler Plastometer fluidity measurements indicates that the plastometer test may be useful in distinguishing between volume-change behavior groups in these coals. These results are in general agreement with the relationship shown by Naugle, Davis, and Wilson¹⁰⁾ for coals ranging from low volatile to high-volatile A.

Volume Change

The volume changes of the 30 samples after carbonization in the sole-heated oven were found to correlate with (1) volatile-matter contents for samples containing similar ash contents and (2) with ash contents for samples with similar volatile matter contents.

The volume change of each of the 5 washed coals used in this program, along with selected Bureau of Mines data¹⁰⁾ is plotted in Figure 4 against the corresponding volatile-matter and ash contents on the dry basis. For the 5 Pratt-seam coals (Mines A, B, and C) and 1 American-seam coal the volume change varied linearly from slightly expanding to strongly contracting as the volatile matter increased for ash contents between about 6 to 9 per cent. This same relationship is also evident for the 3 Mary Lee seam coals, which had a higher level of ash content of 11 to 12 per cent. In contrast to the washed coals, the raw Pratt-seam coals from Mine A, taken from the same site in the mine, and the washed sample from this same mine (all plotted in Figure 5) showed contraction varying linearly with ash content when true volatile-matter contents ranged between 30.8 and 31.8 per cent. These same general relationships were evident for the other coals used in this program except that the individual effects of volatile matter and ash were masked by one another.

General relationships within narrow ranges of volatile matter, similar to those noted above, were reported by Brown³⁾ for Pennsylvania and West Virginia coals; for these it was also shown that separate relationships existed between the expansion and the volatile matter of two low-volatile coals. Later work by Naugle, Davis, and Wilson⁴⁾ also showed this same type of relationship, except that expansion was plotted against the dry, mineral-matter-free fixed-carbon contents of the coals. The fixed-carbon content, calculated on the dry, mineral-matter-free basis should give a similar relationship to that with the true volatile-matter content, because the fixed-carbon content is simply 100 minus the volatile-matter content determined in the proximate analysis.

An examination of the volume-change behavior of the various raw samples in terms of their site and zone locations in the mine provided the following results. In the Pratt Seam Mine A samples, contraction decreased from top to bottom of the seam as the ash contents of the zone samples decreased from top to bottom. These relationships are shown in Figure 6. In the American seam samples the volume change of the Site No. 1 zone samples varied from strongly expanding at the top of the seam, to mildly contracting about one-third down from the top of the seam, and back to moderately expanding in the lower two thirds of the seam, Figure 7. Although the ash contents of these samples were relatively low, the mildly contracting zone had the highest ash content. In the Site No. 2 zone samples from this mine, the top and bottom zones were strongly contracting (about 17 to 20%), whereas the two middle zones were only moderately contracting (about 9%). The ash contents of these samples, all below 8 per cent, more than doubled between top and bottom.

In the Mary Lee Seam samples, the Site No. 1 zone samples changed from mildly contracting at the top of the seam to strongly contracting between about one-fourth and one-half way down from the top, dropped to mildly contracting about three-fourths of the distance from the top, and increased again to strongly contracting at the bottom, Figure 8. The Site No. 2 samples were almost neutral at a bulk density of 55 pounds per cubic foot in the sole-heated oven. The volume change varied from incipiently contracting at the top of the seam to mildly expanding between the top and about one-quarter of the way down from the top of the seam, to mildly contracting between one-quarter and one-third of the way down, to incipiently expanding between two-thirds of the way down from the top and to mildly contracting at the bottom.

Coke Strength

Because there was insufficient coal in each sample for carbonization tests in the Laboratory's 500-pound oven, an attempt was made to evaluate the strengths of the cokes from the sole-heated oven, Table III, and those of the corresponding cokes from the 30-pound test oven, Table IV. These relative strengths were plotted, Figure 9, in terms of the Modified Tumbler Index. The correlation coefficient for the relationship shown in Figure 9 was 0.94. In general, the cokes from the two ovens maintained similar relative positions: coals that produced strong cokes in the one oven also produced strong cokes in the other oven. Because of the wide differences in coking rates in the two ovens, the relationship that is valid for these coals cannot be expected to be generally applicable to other coals, especially to less strongly coking coals.

The influence of the ash contents of the raw and washed coals on the strengths of the test-oven cokes can be distinguished when the data are examined critically, but the full effect is masked and is difficult to establish conclusively because of the interrelationship between the ash content and the degree of pulverization of the various charges, shown in Figure 2. In the present tests, the larger average-particle size of some coals, particularly those in which the inert-type materials present are resistant to pulverization, resulted in more abradable cokes with lower Modified Tumbler Indexes than those produced from coals of smaller particle size, see Tables III and IV. Other coals of relatively high ash content produced cokes of strengths equivalent to or greater than cokes from coals of lower ash content, apparently because the inert materials present in the former were reduced to smaller particle size than those in the latter. When coals of similar ash content, either high or low, showed marked differences in degree of pulverization, those of coarser size-consist usually yielded test-oven cokes of lower strength.

Summary

The chief results of this investigation of the possible correlations existing between the carbonization behavior of these coals and their chemical and plastic properties were as follows:

(1) All coals, both raw and washed, can be classified in two broad fluidity and volume-change groups: (a) those showing fluidities above 10,000 ddpm, all of which were contracting, and (b) those below 10,000 ddpm, but above approximately 2500 ddpm, which were mildly contracting, neutral, or moderately expanding. Thus, measurement of fluidity in the Gieseler plastometer may be a means of classifying similar coals into at least two broad groups, according to the relative volume change observed in the sole-heated oven.

(2) For ash contents within narrow limits and for the range of volatile-matter contents determined in these coals, volume change in the sole-heated oven showed a linear change with dry-basis volatile-matter content. Likewise, for coals of a narrow range of true volatile-matter contents, contraction increased with increasing ash content. Consequently, it should be possible to correlate the volume change of these coals with their chemical properties. However, because variations existed in the raw and washed coals from the various seams used in this investigation, and are known to exist in practice, it is natural to expect variations in both the volatile-matter and the ash contents of these coals. It would appear, therefore, that a useful method of estimating the comparative pushing characteristics of these coals from an examination of their chemical properties should result from the use of the relative volume change obtained from a multiple correlation with corrected ash and volatile-matter contents.

(3) A significant correlation existed between the Modified Tumbler Indexes of the cokes produced in the sole-heated oven and those produced in the 30-pound test oven.

(4) The influence of ash content on coke strength was evident. However, the separate and full effect of ash content was masked by particle size, which has an important influence on coke strength, because increased ash content in the samples tested also indicated an increased amount of coarse, pulverization-resistant, inert-type, intermediate-gravity materials in the coal. The practical significance of this relationship is probably limited because the washed coals used in practice have ash contents that may not vary enough to appreciably affect the coke strength.

References

1. Gayle, J. B.; Eddy, W. H.; Brooks, J. A., "Studies of Coal Expansion," Chemical Engineering and Manufactured Gas Production Conference, Operation Section, American Gas Association, May 24 - 26, 1954, Pittsburgh, Pa., CEP-54-5.
2. Brisse, A. H., "Determination of Coke Oven Productivity From Coal Charge Characteristics," Blast Furnace and Steel Plant, Vol. 47, No. 4, April, 1959, pp. 376 - 383.
3. Brown, W. T., "Coal Expansion," Blast Furnace and Steel Plant, Vol. 30, January 1942, pp. 67 - 71, 219 - 23, 226.
4. Naugle, B. W.; Davis, J. D.; and Wilson, J. E., "Precision of Expansion Tests on Coal," Industrial and Engineering Chemistry, Vol. 43, December, 1951, pp. 2916 - 2922.
5. Price, J. G.; Shoenberger, R. W.; and Perlic, B., "Use of a Thirty-Pound Test Oven for Rapidly Assaying the Coking Strength of Coals," Blast Furnace, Coke Oven and Raw Materials Committee Proceedings, AIME (1958) Vol. 17, pp. 212 - 222.
6. Brown, W. T.; Coal Expansion: Proceedings American Gas Association, 1938, pp. 640 - 679.
7. Parr, S. W., Fuel, Gas, Water and Lubricants, 4th Edition, McGraw-Hill Book Co., New York, N. Y., pp. 49 - 55.
8. Naugle, B. W.; Wilson, J. E.; and Smith, F. W.; "Expansion of Coal in Sole-Heated Oven," U. S. Bureau of Mines, Report of Investigation 5295, January, 1957.
9. ASTM Designation: D388-38, Standard Specification for Classification of Coals by Rank.
10. Wilson, J. E.; Naugle, B. W.; and Wolfson, D. E.; "Expanding Properties of American Coals Tested in a Sole-Heated Oven," U. S. Bureau of Mines, Report of Investigation 5537, 1959.

Table I

Proximate Analyses and Calculated Mineral-Matter Contents (Dry Basis)

Coal		Proximate Analysis,				Calculated Mineral Matter, wt %
		wt %		Ash	Sulfur, wt %	
		Volatile Matter	Fixed Carbon			
<u>American Seam</u>						
Washed		26.7	65.8	7.5	0.9	8.6
Site No. 1	Zone 1	23.6	72.7	3.7	0.9	4.5
(Raw)	Zone 2	23.9	73.0	3.1	0.8	3.7
	Zone 3	22.9	66.4	10.7	1.0	12.1
	Zone 4	23.3	71.6	5.2	0.8	6.1
	Zone 5	24.6	69.8	5.6	1.1	6.7
Site No. 2	Zone 1	30.4	66.3	3.3	0.6	3.9
(Raw)	Zone 2	29.8	64.8	5.4	0.7	6.2
	Zone 3	30.3	65.2	4.5	0.6	5.2
	Zone 4	29.7	63.3	7.0	0.7	8.0
	Full Seam	30.0	63.5	6.5	0.6	7.4
<u>Pratt Seam, Mine A</u>						
Washed		30.2	62.3	7.5	1.7	8.3
Site No. 1	Zone 1	28.6	54.9	16.5	5.6	20.9
(Raw)	Zone 2	28.9	61.9	9.2	1.7	10.9
	Zone 3	30.4	66.2	3.4	1.7	4.6
	Zone 4	30.4	65.2	4.4	1.9	5.8
	Full Seam	27.5	57.6	14.9	2.1	17.3
<u>Mary Lee Seam</u>						
Washed		27.6	60.7	11.7	0.8	13.1
Site No. 1	Zone 1	29.0	58.6	12.4	0.7	13.8
(Raw)	Zone 2	28.3	54.0	17.7	1.1	19.7
	Zone 3	27.0	47.4	25.6	1.1	28.3
	Zone 4	29.5	61.3	9.2	0.6	10.3
	Zone 5	28.4	52.8	18.8	0.6	20.6
Site No. 2	Zone 1	24.8	59.1	16.1	1.8	18.4
(Raw)	Zone 2	24.9	60.8	14.3	0.6	15.8
	Zone 3	25.2	57.0	17.8	0.9	19.7
	Zone 4	25.1	62.6	12.3	0.6	13.6
	Zone 5	27.2	65.8	7.1	0.7	8.1
<u>Pratt Seam, Mine B</u>						
Washed		26.1	67.0	7.0	1.3	8.3
<u>Pratt Seam, Mine C</u>						
Washed		28.0	63.6	8.4	1.7	10.0

Table II
Plastic Properties

Coal		Gieseler*		Plastic Range, C	
		Maximum Fluidity		Softening	Solidification
		Dial Divisions			
		Per Min	At C	Temperature	Temperature
<u>American Seam</u>					
Washed		7,400	449	380	515
Site No. 1 (Raw)	Zone 1	4,000	458	391	504
	Zone 2	3,400	454	385	503
	Zone 3	3,800	459	390	502
	Zone 4	2,800	476	390	506
	Zone 5	2,700	450	385	505
Site No. 2 (Raw)	Zone 1	18,500	438	376	494
	Zone 2	12,000	439	371	482
	Zone 3	18,500	437	371	493
	Zone 4	16,500	434	375	-
	Full Seam	18,500	442	373	494
<u>Pratt Seam, Mine A</u>					
Washed		16,500	436	348	496
Site No. 1 (Raw)	Zone 1	14,000	432	350	489
	Zone 2	20,000	437	356	503
	Zone 3	17,500	432	355	486
	Zone 4	20,500	434	354	497
	Full Seam	19,000	437	357	500
<u>Mary Lee Seam</u>					
Washed		9,500	442	362	495
Site No. 1 (Raw)	Zone 1	12,500	448	371	490
	Zone 2	15,000	441	370	491
	Zone 3	21,500	442	370	484
	Zone 4	12,000	447	361	490
	Zone 5	14,000	436	363	489
Site No. 2 (Raw)	Zone 1	3,500	444	367	499
	Zone 2	3,500	458	369	500
	Zone 3	5,000	446	364	498
	Zone 4	7,000	444	371	494
	Zone 5	8,500	446	362	497
<u>Pratt Seam, Mine B</u>					
Washed		6,000	449	391	502
<u>Pratt Seam, Mine C</u>					
Washed		13,000	439	368	500

* No washer was used on the Gieseler plastometer retort to prevent swelling.

Table III

Sole-Heated Oven Test Results

Coal	Volume Change (as Measured), %		Oven Bulk Density,* lb/cu ft	Corrected Volume Change, % (at 55 lb/cu ft)	Modified Tumbler Index of Coke Cum % + 3/4 in.
	Maximum	Final			
<u>American Seam</u>					
Washed		-4.1	55	-2.9	75
Site No. 1	Zone 1	-3.8	48	+11.3	74
(Raw)	Zone 2	+1.5	51	+7.9	77
	Zone 3	-7.8	53	-2.7	56
	Zone 4	-3.6	51	+7.8	75
	Zone 5	+1.0	52	+5.9	69
Site No. 2	Zone 1	-20.6	48	-17.1	62
(Raw)	Zone 2	-13.5	48	-9.1	58
	Zone 3	-18.7	50	-8.9	66
	Zone 4	-27.8	51	-20.7	43
	Full Seam	-18.8	50	-9.0	57
<u>Pratt Seam, Mine A</u>					
Washed		-25.2	52	-20.1	68
Site No. 1	Zone 1	-32.2	56	-31.9	55
(Raw)	Zone 2	-27.7	52	-22.8	36
	Zone 3	-20.6	52	-14.7	72
	Zone 4	-15.4	52	-10.3	72
	Full Seam	-30.0	56	-29.9	14
<u>Mary Lee Seam</u>					
Washed		+0.3	54	0.0	73
Site No. 1	Zone 1	-9.1	53	-3.4	58
(Raw)	Zone 2	-20.6	56	-19.9	24
	Zone 3	-21.4	58	-21.8	43
	Zone 4	-12.1	51	-4.4	67
	Zone 5	-24.3	53	-20.0	18
Site No. 2	Zone 1	-5.1	53	-0.6	74
(Raw)	Zone 2	+1.3	53	+3.5	70
	Zone 3	-8.0	54	-4.9	46
	Zone 4	-3.4	53	+0.8	69
	Zone 5	-7.2	53	-3.2	69
<u>Pratt Seam, Mine B</u>					
Washed		+3.1	55	+1.6	75
<u>Pratt Seam, Mine C</u>					
Washed		-9.0	55	-8.1	72

* One % moisture content.

Table IV

Coking-Pressure and Modified-Tumbler-Index Results
(Conducted in 30-Pound Test Oven)

<u>Coal</u>		<u>Coking Pressure, psi</u>	<u>Oven Bulk Density,* lb/cu ft</u>	<u>Modified Tumbler Index cum % • 3/4 in.</u>
<u>American Seam</u>				
Washed		1.0	47	68
Site No. 1	Zone 1	1.0	44	71
(Raw)	Zone 2	1.2	46	66
	Zone 3	1.6	46	54
	Zone 4	1.9	45	64
	Zone 5	0.9	45	65
Site No. 2	Zone 1	0.6	45	58
(Raw)	Zone 2	1.0	45	62
	Zone 3	0.7	48	61
	Zone 4	0.8	44	59
	Full Seam	0.6	44	58
<u>Pratt Seam, Mine A</u>				
Washed		1.5	48	65
Site No. 1	Zone 1	1.2	47	62
(Raw)	Zone 2	1.0	46	50
	Zone 3	-	-	-
	Zone 4	1.6	45	62
	Full Seam	0.9	48	24
<u>Mary Lee Seam</u>				
Washed		2.1	49	70
Site No. 1	Zone 1	1.0	45	58
(Raw)	Zone 2	1.0	48	41
	Zone 3	1.4	50	50
	Zone 4	1.3	46	61
	Zone 5	1.4	47	26
Site No. 2	Zone 1	2.8	48	72
(Raw)	Zone 2	2.3	46	68
	Zone 3	1.0	49	50
	Zone 4	-	-	-
	Zone 5	1.0	45	70
<u>Pratt Seam, Mine B</u>				
Washed		-	-	-
<u>Pratt Seam, Mine C</u>				
Washed		1.0	47	65

* One % moisture content.

Figure No. 1

EFFECT OF ASH CONTENT ON BULK DENSITY

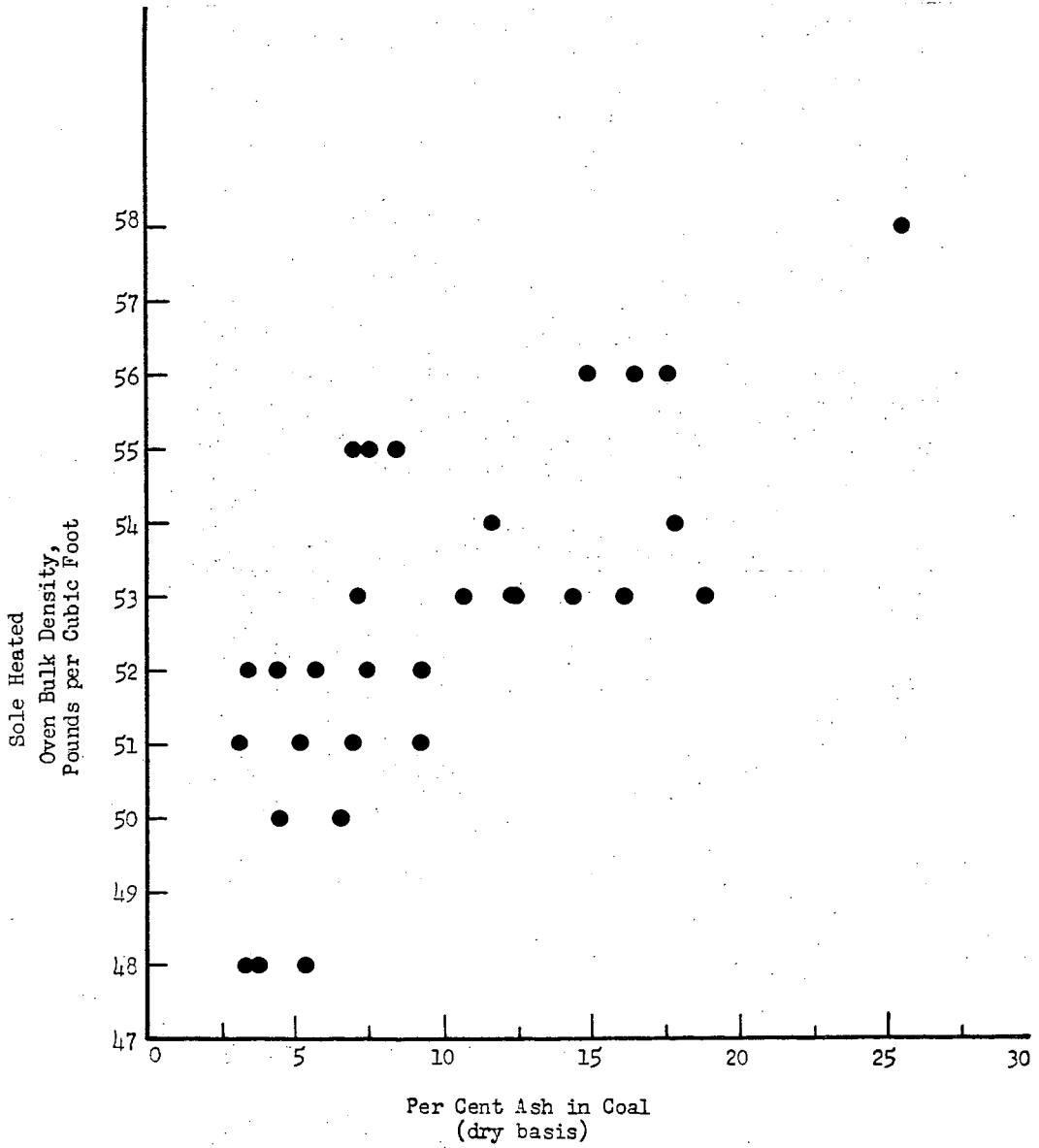


Figure No. 2

EFFECT OF ASH CONTENT ON PULVERIZATION (PER CENT RETAINED ON 8-MESH)

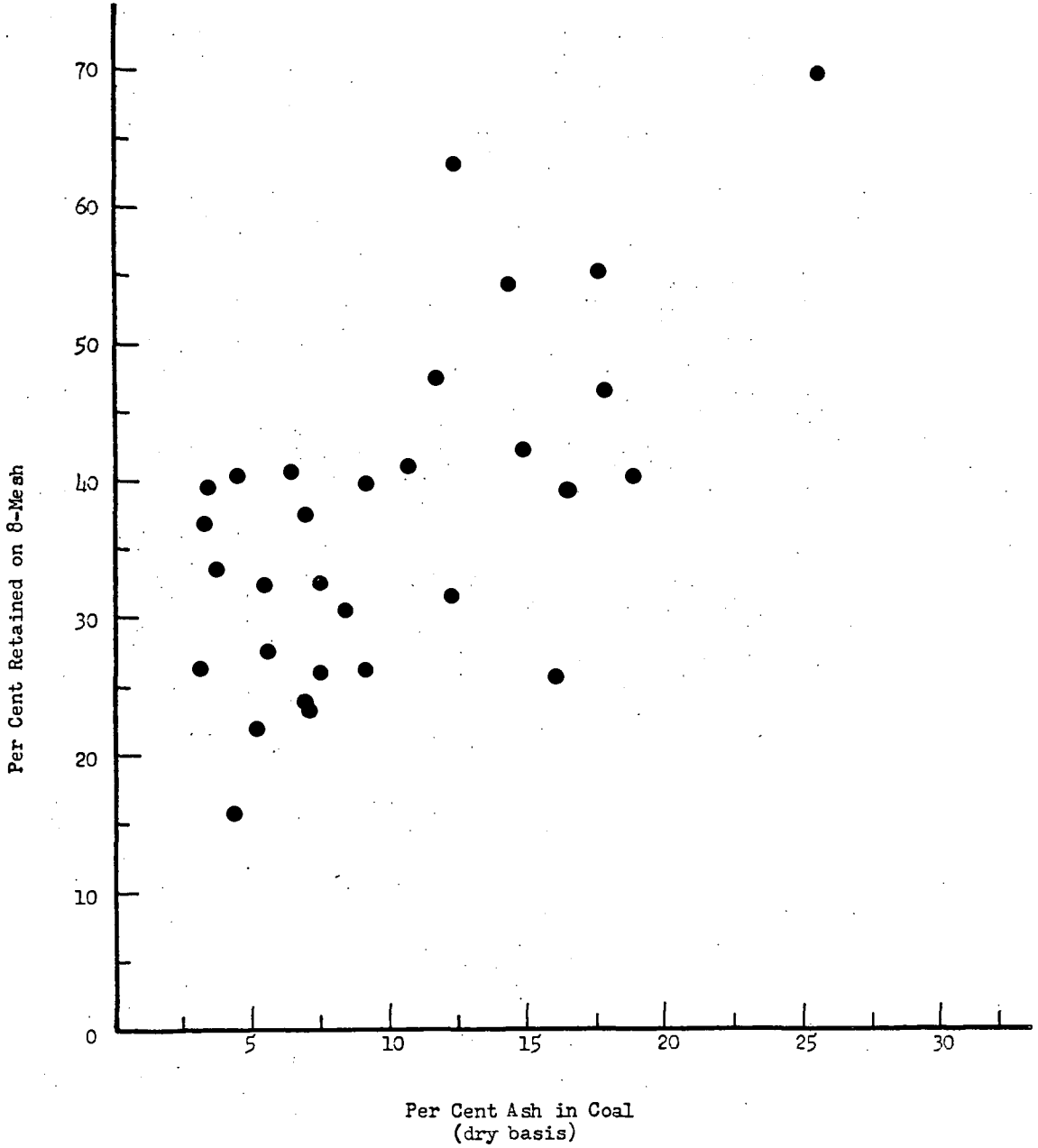


Figure No. 3

RELATIONSHIP OF VOLUME CHANGE IN THE SOLE-HEATED OVEN AND MAXIMUM FLUIDITY

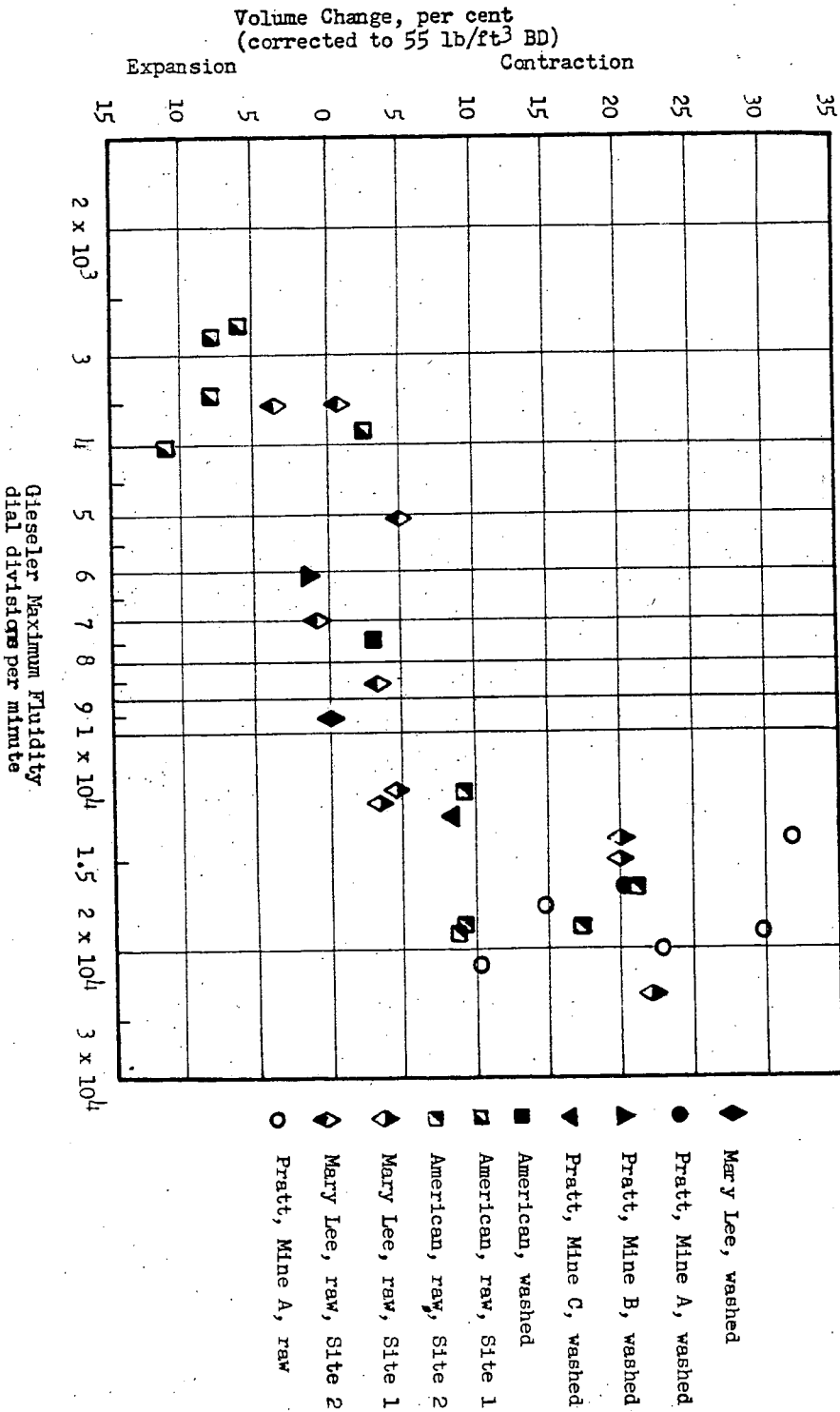


Figure No. 4

RELATIONSHIP OF VOLUME CHANGE IN THE SOLE-HEATED OVEN TO VOLATILE MATTER AND
ASH CONTENTS OF WASHED COALS

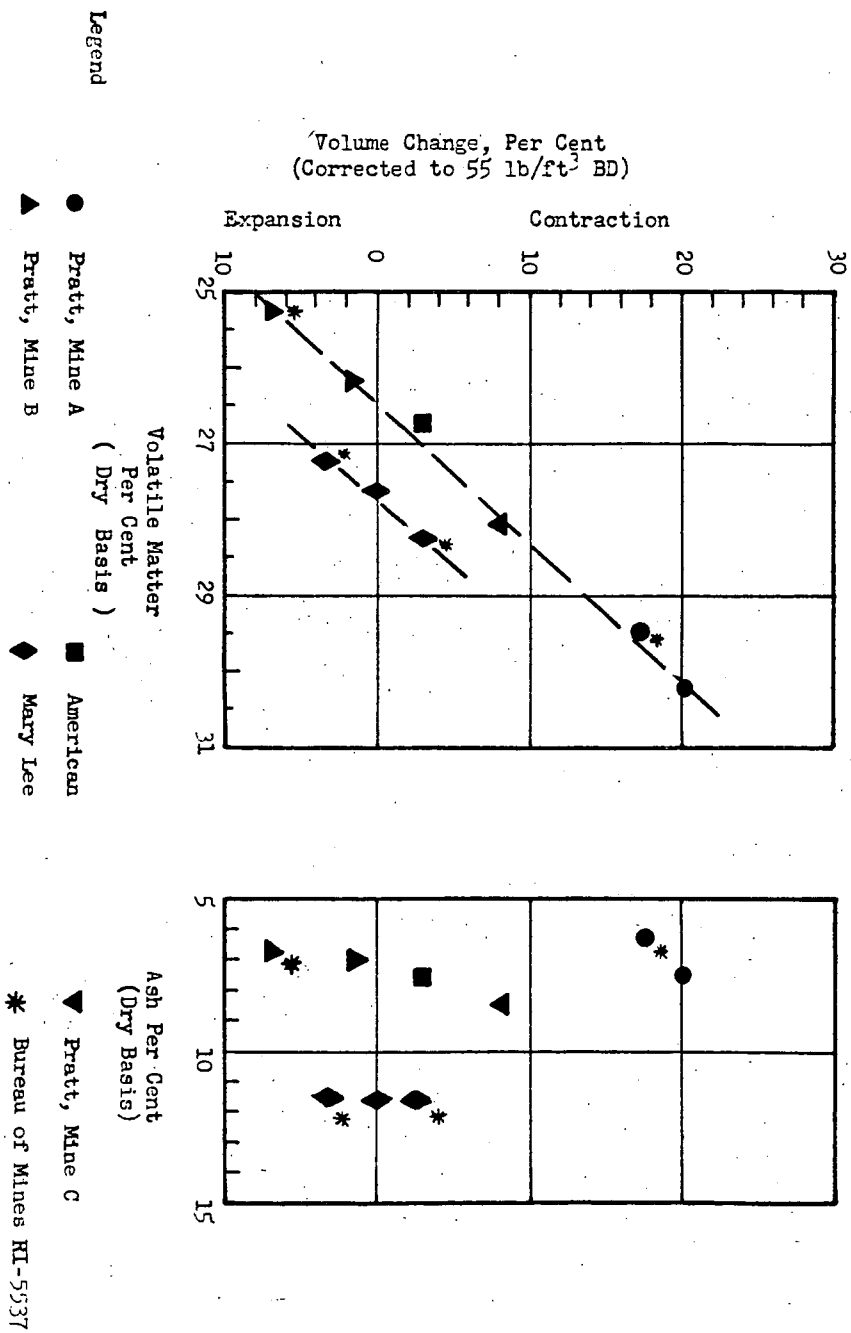


Figure No. 5

RELATIONSHIP OF CONTRACTION IN THE SOLE-HEATED OVEN TO ASH AND VOLATILE MATTER CONTENTS
OF PRATT SEAM MINE A, COALS

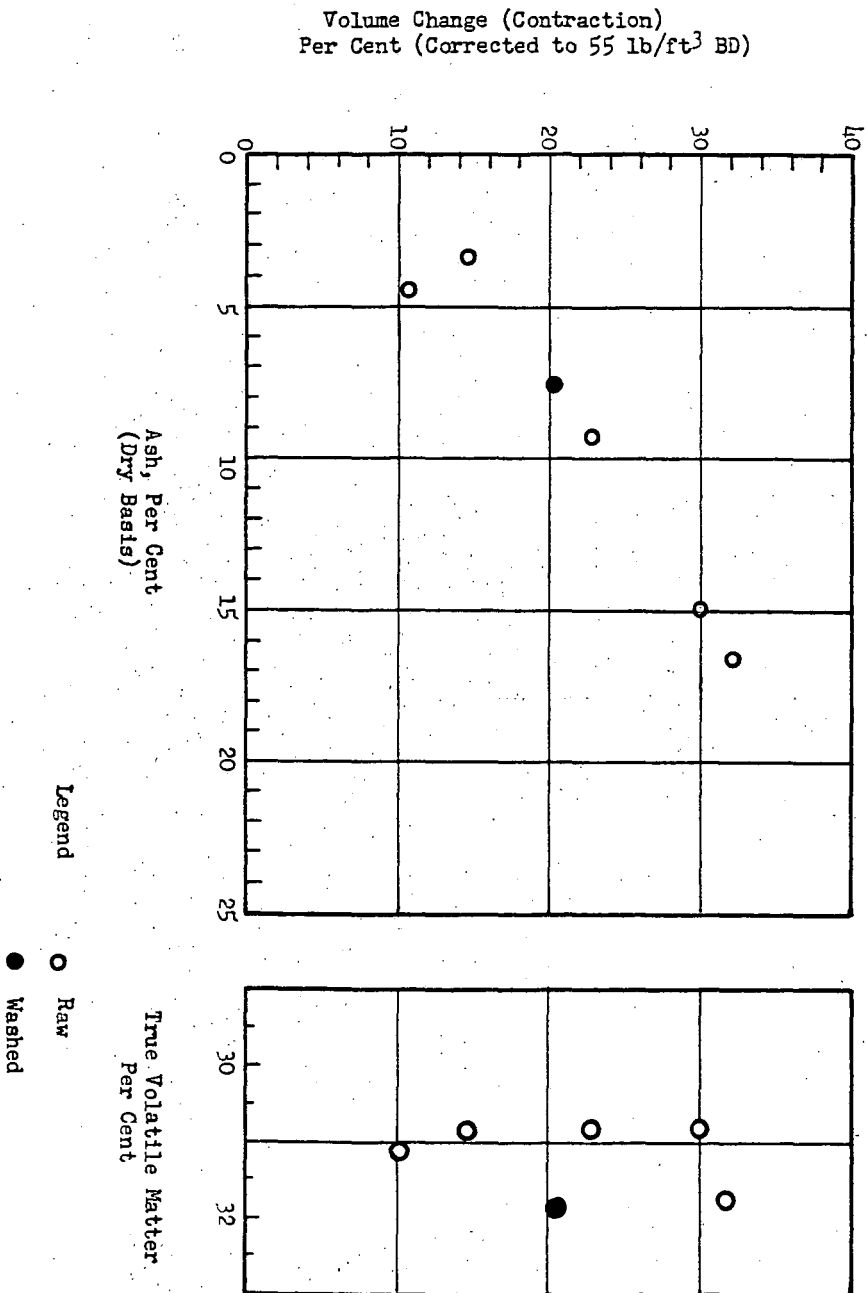


Figure No. 7

COMPARISON OF SITE AND ZONE SAMPLES FROM AMERICAN SEAM MINE

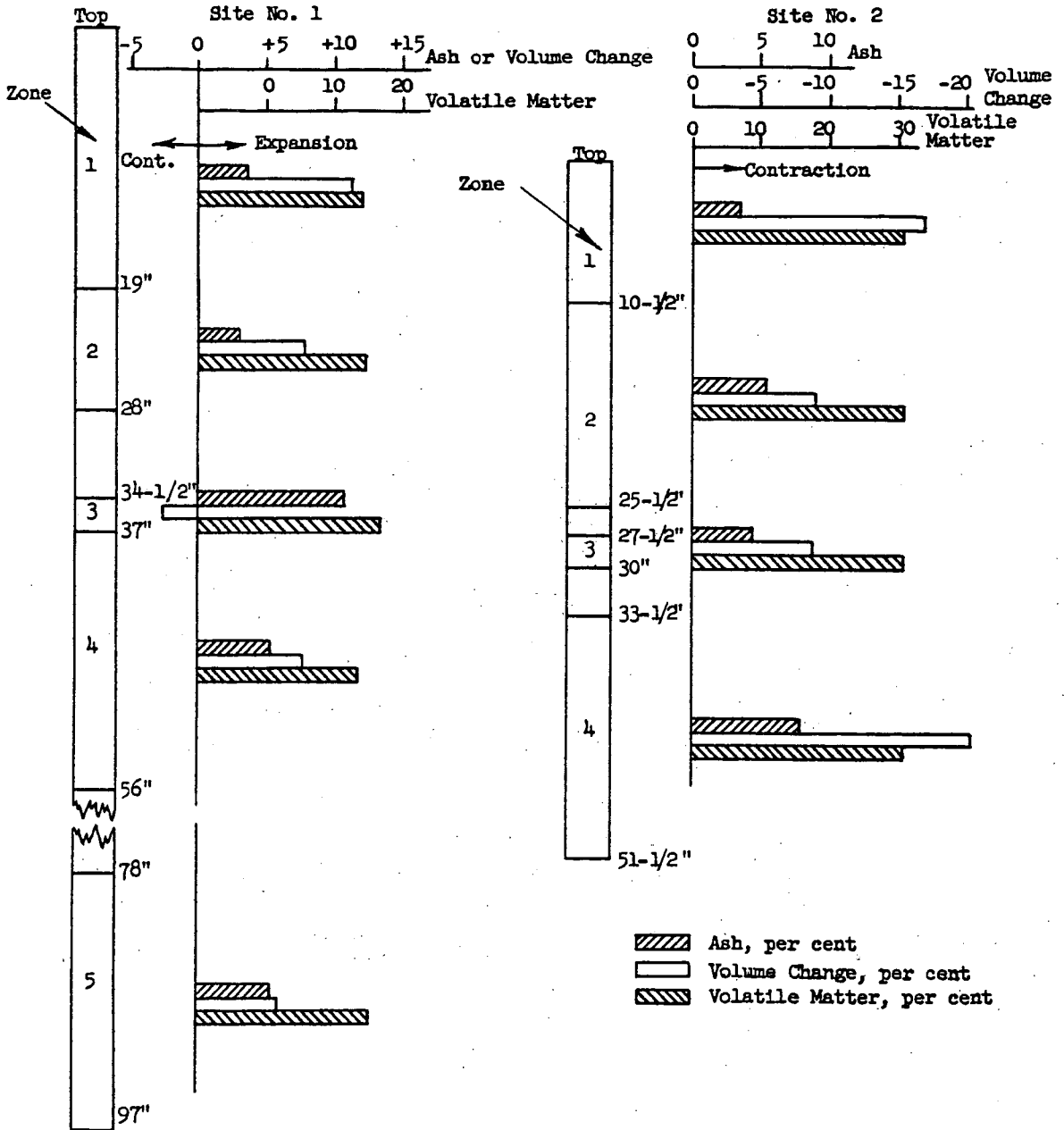


Figure No. 6

COMPARISON OF ZONE SAMPLES FROM THE PRATT SEAM, MINE A

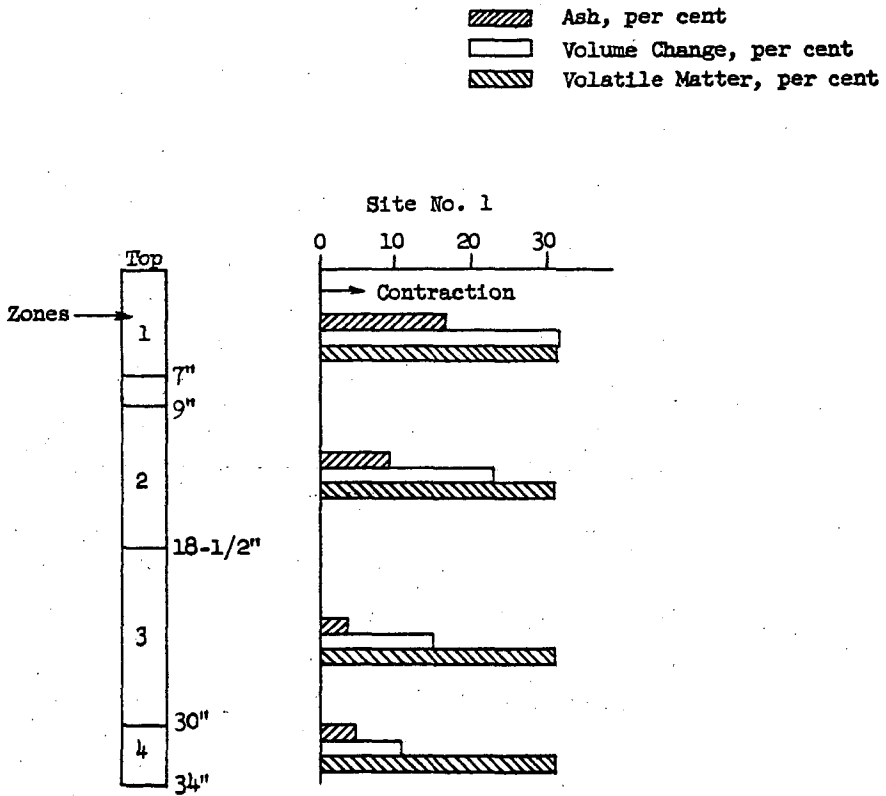


Figure No. 8

COMPARISON OF SITE AND ZONE SAMPLES FROM MARY LEE SEAM MINE

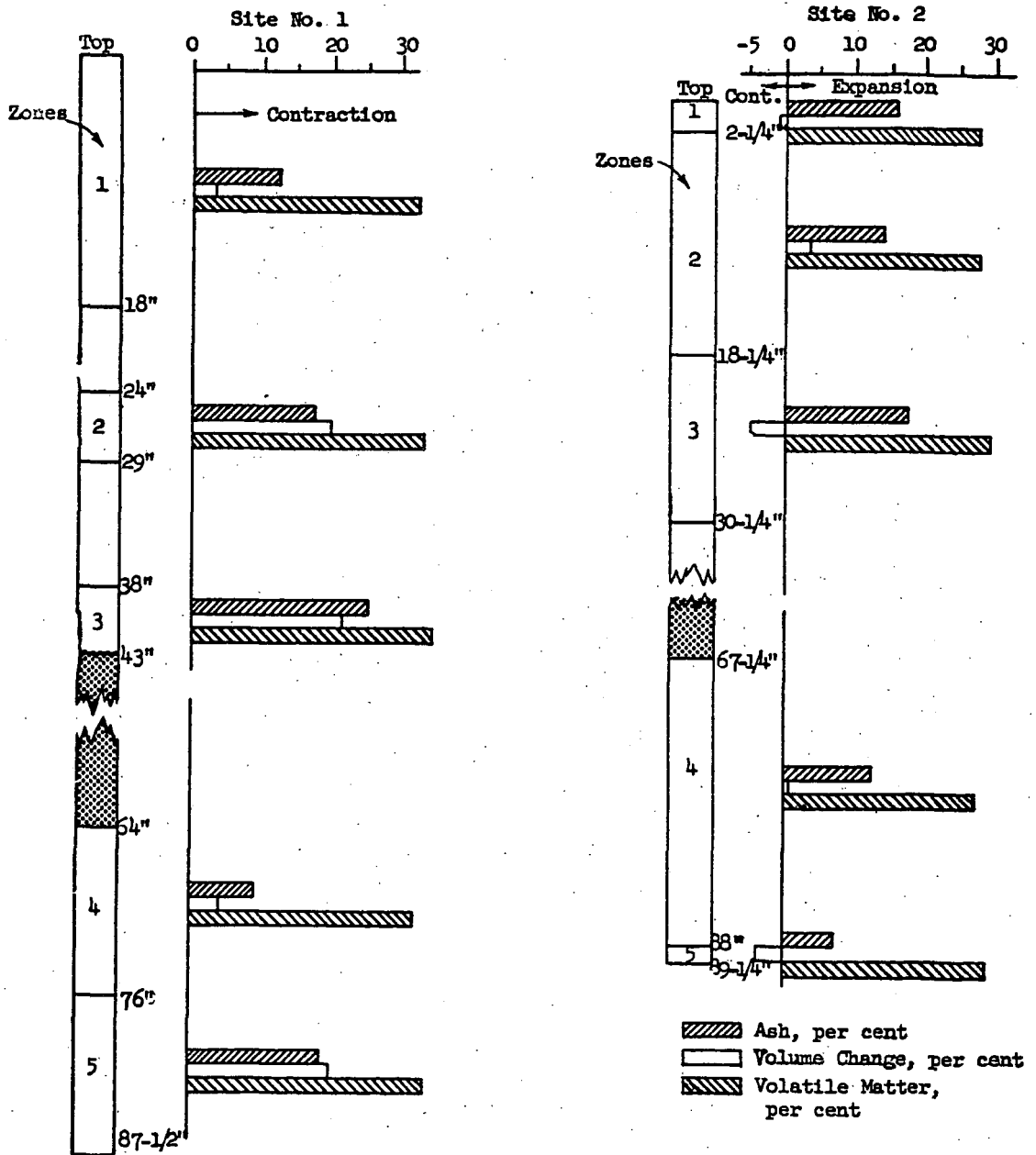


Figure No. 9

RELATIONSHIP BETWEEN 30 POUND TEST AND SOLE-HEATED OVENS 3/4-INCH
TUMBLER INDEXES

